ERDC/CHL TR-11-1

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

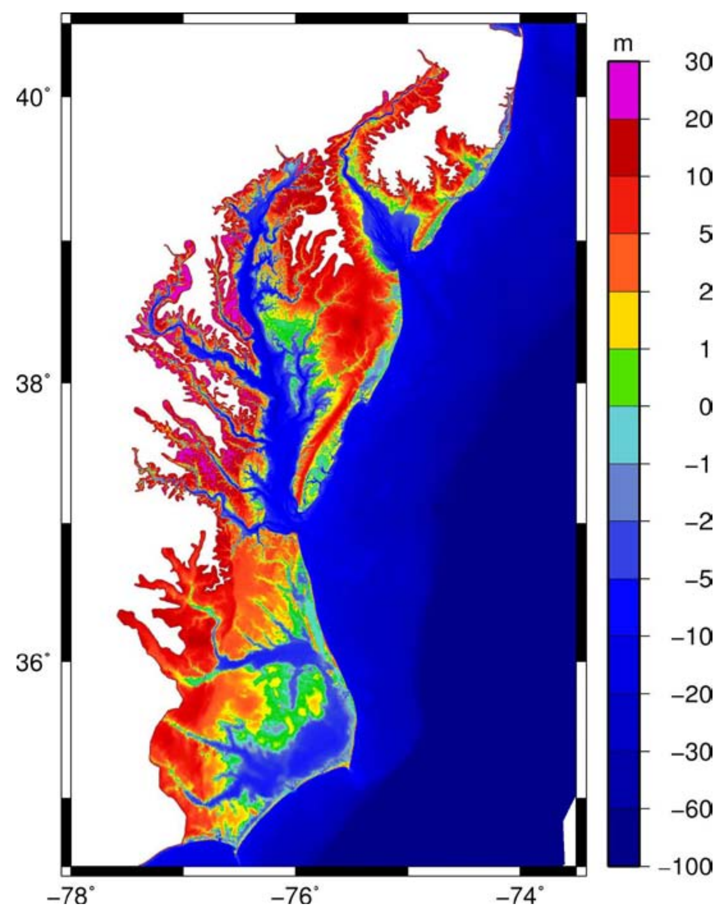
*FEMA Region III Storm Surge Study*

# Coastal Storm Surge Analysis: Computational System

## Report 2: Intermediate Submission No. 1.2

Brian Blanton, Lisa Stillwell, Hugh Roberts, John Atkinson, Shan Zou, Michael Forte, Jeffrey Hanson and Rick Luettich

March 2011



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Report 2 of a series



Prepared for Federal Emergency Management Agency

Under U.S. Army Corps of Engineers Work Unit J64C87

**Abstract:** The Federal Emergency Management Agency, Region III office, has initiated a study to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia including the Atlantic Ocean, Chesapeake Bay including its tributaries, and the Delaware Bay. This effort is one of the most extensive coastal storm surge analyses to date, encompassing coastal floodplains in three states and including the largest estuary in the world. The study will replace outdated coastal storm surge stillwater elevations for all Flood Insurance Studies in the study area, and serve as the basis for new coastal hazard analysis and ultimately updated Flood Insurance Rate Maps (FIRMs). Study efforts were initiated in August of 2008, and are expected to conclude in 2011.

The storm surge study will utilize the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional hydraulics. ADCIRC will be coupled with 2-dimensional wave models to calculate the combined effects of surge and wind-induced waves. A seamless modeling grid was developed to support the storm surge modeling efforts. This report, the second of three reports comprising the required Submittal 1 documentation, provides a detailed overview of the construction of the modeling mesh and the development of an integrated computational system for FEMA Region III storm surge modeling.

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# Preface

This study was conducted for the Federal Emergency Management Agency (FEMA) under Project HSFE03-06-X-0023, “NFIP Coastal Storm Surge Model for Region III.” The technical monitor was Ms. Robin Danforth.

The work was performed by the Coastal Processes Branch (HF-C) of the Flood and Storm Protection Division (HF), U.S. Army Engineer Research and Development Center –Coastal & Hydraulics Laboratory (ERDC-CHL). At the time of publication, Dr. Ty V. Wamsley was Chief, CEERD-HF-C; Bruce Ebersole was Chief, CEERD-HF; and Dr. Jeffrey L. Hanson was the Project Manager. The Deputy Director of ERDC-CHL was Jose E. Sanchez and the Director was Dr. William D. Martin.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| cubic yards | 0.7645549 | cubic meters |
| feet | 0.3048 | meters |
| miles (U.S. statute) | 1,609.347 | meters |

# 1 Overview

The Federal Emergency Management Agency (FEMA) is responsible for preparing Federal Insurance Rate Maps (FIRMs) that delineate flood hazard zones in coastal areas of the United States. Under Task Order HSFE03-06-X-0023, the US Army Corps of Engineers (USACE) and project partners are assisting FEMA in the development and application of a state-of-the-art storm surge risk assessment capability for the FEMA Region III domain which includes the Delaware Bay, Chesapeake Bay, District of Columbia, Delaware-Maryland-Virginia Eastern Shore, Virginia Beach, and all tidal tributaries and waterways connected to these systems. The goal is to develop and apply a complete end-to-end modeling system, with all required forcing inputs, for updating the floodplain levels for coastal and inland watershed communities. Key components of this work include:

1. Develop a high-resolution DEM for Region III, and convert this to an unstructured modeling grid, with up to 50-m horizontal resolution, for use with the production system.
2. Define the Region III storm hazard in terms of historical extratropical storms and synthetic hurricanes selected using the Joint Probability Method with Optimum Sampling (JPM-OS) (Niedoroda et al., 2010)
3. Prepare an end-to-end modeling system for assessment of Region III coastal storm surge hazards
4. Verify model accuracy on a variety of reconstructed tropical and extratropical storm events
5. Apply the modeling system to compute the 10-, 50-, 100-, and 500- year floodplain levels
6. Develop a database with Geographic Information System (GIS) tools to facilitate archiving, distribution, and analysis of the various storm surge data products

Under the direction of FEMA Region III Program Manager Ms. Robin Danforth, USACE assembled a multi-organization partnership to meet the Region III objectives. Work on this project benefited from the experience acquired during the setup of the North Carolina Floodplain Mapping Program (NCFMP) storm surge modeling system. The availability of the NCFMP storm surge modeling system has resulted in a significant cost savings for FEMA Region III. Experts in the fields of coastal storm surge, wind-driven waves, GIS, and high-performance computational systems have worked together in this effort. The project partners and their primary roles are listed in Table 1.1.

Table 1.1 Expert team.

| Organization | Contacts | Primary Role(s) |
|---|---|---|
| US Army Engineer Research & Development Center<br>Coastal & Hydraulics Laboratory<br>Field Research Facility | Jeff Hanson<br>Mike Forte<br>Heidi Wadman | Project Manager<br>DEM Construction<br>Model Validations |
| Applied Research Associates/IntraRisk (ARA) | Peter Vickery | Simulated Hurricanes |
| ARCADIS | Hugh Roberts<br>John Atkinson<br>Shan Zou | Modeling Mesh<br>Modeling Mesh<br>Modeling Mesh |
| Elizabeth City State University | Jinchun Yuan | Web/GIS |
| Oceanweather, Inc. | Vince Cardone<br>Andrew Cox | Wind/Pressure Field Reconstructions |
| Renaissance Computing Institute (RENCI) | Brian Blanton<br>Lisa Stillwell<br>Kevin Gamiel | Modeling System<br>DEM Construction<br>Database/Web/GIS |
| University of North Carolina- Chapel Hill (UNC-CH) | Rick Luettich<br>Crystal Fulcher | Science Consultant<br>Modeling Mesh |
| US Army Corps of Engineers<br>District Offices (NAP, NAO, NAB) | Jason Miller<br>Paul Moye<br>Jared Scott | Bathy/Topo Data Inventory |

In addition to the expert team, a Technical Oversight Group provided guidance and input to all project phases. This group included members from the following organizations:

- Chesapeake Bay Research Consortium
- Delaware Flood Mitigation Program
- Federal Emergency Management Agency
- Dewberry, Inc.
- North Carolina Floodplain Mapping Program
- US Army Engineer Research and Development Center

This report (Submittal 1.2) is the second of three stand-alone reports that comprise the documentation set required for Intermediate Submission No. 1 – Scoping and Data Review. The contents of each Submittal are listed in Table 1.2. Guidelines for study conduct and documentation appear in FEMA (2007).

**Table 1.2. Contents of the Submittal 1 reports.**

| Submittal | Title | Contents |
|---|---|---|
| 1.1 | FEMA Region III Coastal Storm Surge Analysis: Study Area and Digital Elevation Model (DEM) | Project Overview<br>Study Area<br>DEM Development |
| 1.2 | FEMA Region III Coastal Storm Surge Analysis: Computational System | Modeling System<br>Mesh Development |
| 1.3 | FEMA Region III Coastal Storm Surge Analysis: Storm Forcing | Hurricane Parameters<br>Extratropical Storms |

The following sections describe the development of a state-of-the-art computational system for this domain. A high-resolution unstructured numerical modeling mesh provides the basis for the modeling system. A high-performance computing environment is used to host a state-of-the-art integrated modeling system for characterizing winds, waves and storm surge in the FEMA Region III coastal domain.

# 2 Modeling Grid

The FEMA_R3_2010 model is an extension of the earlier North Atlantic Model used in the NC mesh (Luettich and Blanton, 2008), *EC2001* U.S. East Coast and Gulf of Mexico tide model (Mukai et al., 2002) and the FEMA Coastal North Carolina storm surge model (Luettich and Blanton, 2008). These models all incorporate the western North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea to allow for full dynamic coupling between oceans, continental shelves, and the coastal floodplain without necessitating that these complicated couplings be defined in the boundary conditions. The FEMA_R3_2010 model extends the geographic coverage of these earlier models to include all the floodplains of coastal Virginia; Maryland; Delaware; Chester County, Delaware County, Philadelphia County and Bucks County, Pennsylvania; and Salem County, Cumberland County and Cape May County, New Jersey. Mesh topography is resolved along the coast from Surf City, New Jersey to Morehead City, North Carolina.

The development of an accurate unstructured finite element mesh for a storm surge model requires appropriate selection of the model domain and optimal resolution of features controlling surge propagation. The FEMA_R3_2010 model domain, shown on Figure 2.1, has an eastern open ocean boundary that lies along the 60-degree west meridian, extending south from the vicinity of Glace Bay in Nova Scotia, Canada, to the vicinity of Coracora Island in eastern Venezuela (Blain et al., 1994; Westerink et al., 1994b; Mukai et al., 2002; Westerink et al., 2008). This domain has a superior open ocean boundary that is primarily located in the deep ocean and lies outside of any resonant basin. There is little geometric complexity along this boundary. Tidal response is dominated by the astronomical constituents, nonlinear energy is limited due to the depth, and the boundary is not located near tidal amphidromes. Hurricane storm surge response along this boundary is essentially an inverted barometric pressure effect correlated directly to the atmospheric pressure deficit in the meteorological forcing; it can therefore be easily specified. This boundary allows the model to accurately capture basin-to-basin and shelf-to-basin physics.

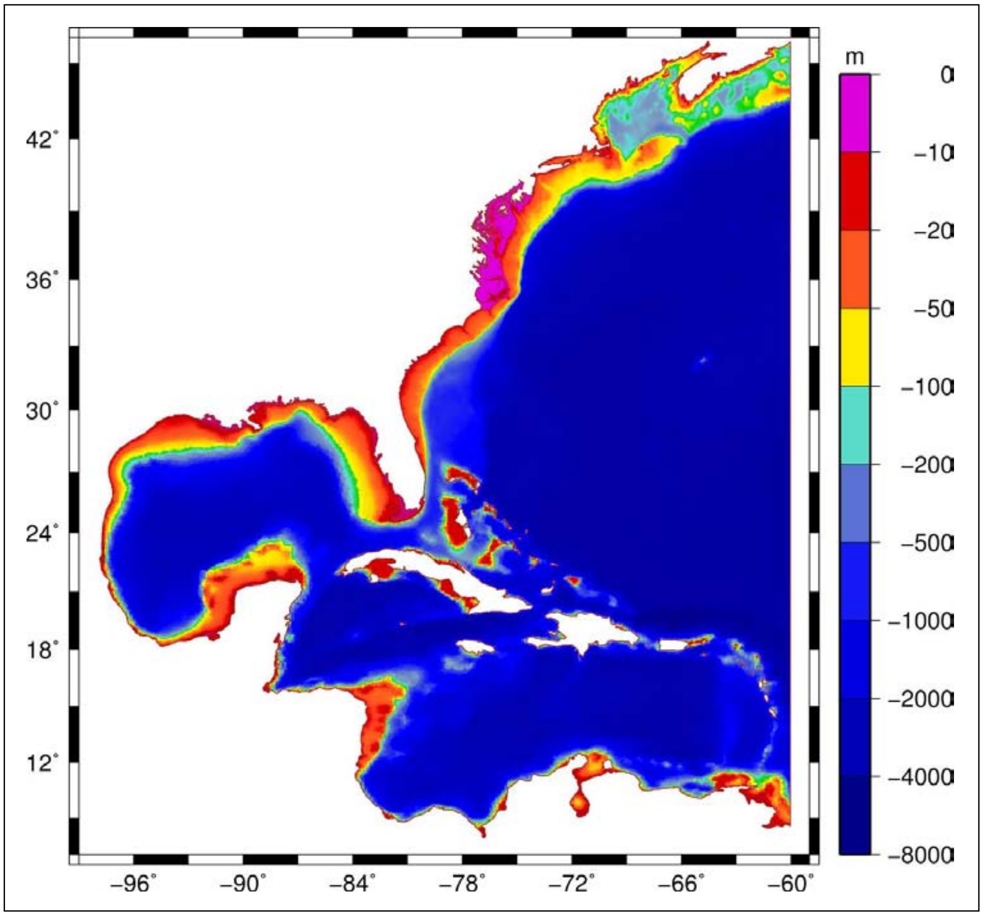


Figure 2.1 ADCIRC mesh domain and elevation contours, meters NAVD88. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

Much of the domain is bordered by a land boundary made up of the eastern coastlines of North, Central, and South America. The highly detailed/resolved region fully encompasses the FEMA Region III domain. In addition, the coastal regions adjacent to the study area, Morehead City, North Carolina to Surf City, New Jersey, were included at high resolution to allow storm surge to realistically propagate into the adjacent regions. Details of the domain with bathymetry and topography, including raised features such as roadways, can be seen on Figures 2.2 through 2.7. The inland extent of the ADCIRC model follows high topography or major hydraulic controls. The land boundary runs along the 15- to 20-meter NAVD88 land contour. The boundary was positioned such that lower-lying valleys and the adjacent highlands were included. It is critical that boundary location and boundary condition specification do not hinder physically realistic model response.

We have incorporated critical hydraulic features and controls that both enhance and attenuate storm surge. Rivers and channels can be conduits for storm surge propagation far inland. Topographical features such as highways impede flow and can focus storm surge energy into local areas, resulting in the amplification of storm surge. Floodplains and wetlands cause attenuation of flood wave propagation. In the study area, there are many interconnected features including Chesapeake and Delaware Bays, naturally scoured and dredged channels, wetlands, and an extensive and intricate system of rivers, bays, high population centers and raised roadways. We have incorporated rivers in the region which are at least 100 meters wide such that they are resolved with the minimum mesh resolution. These rivers include but are not limited to the James River, Rappahannock River, Potomac River and Delaware River. All significant coastal dunes, elevated roads, and railways have been specifically incorporated into the domain as a continuous row of elevated nodes.

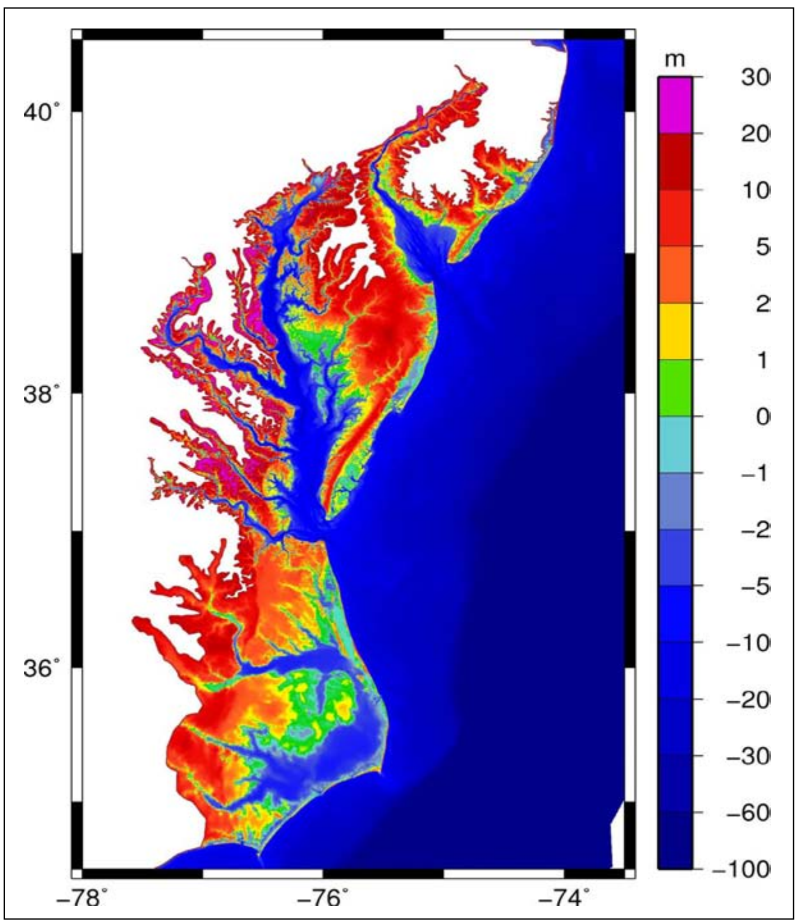


Figure 2.2 ADCIRC mesh elevation contours, meters NAVD88, of the FEMA Region III domain. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

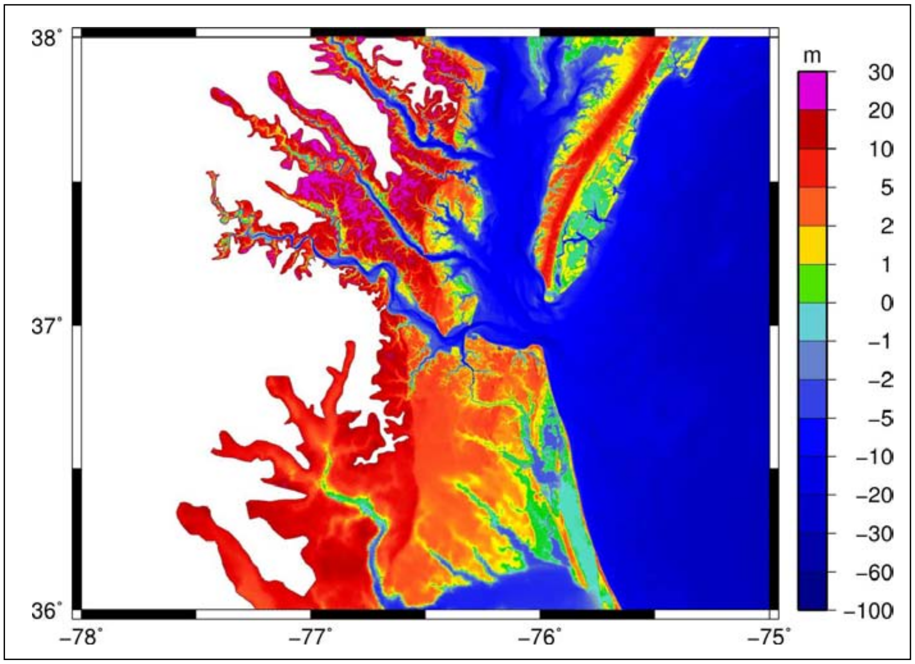


Figure 2.3 ADCIRC mesh elevation contours, meters NAVD88, of the southern portion of the FEMA Region III domain. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

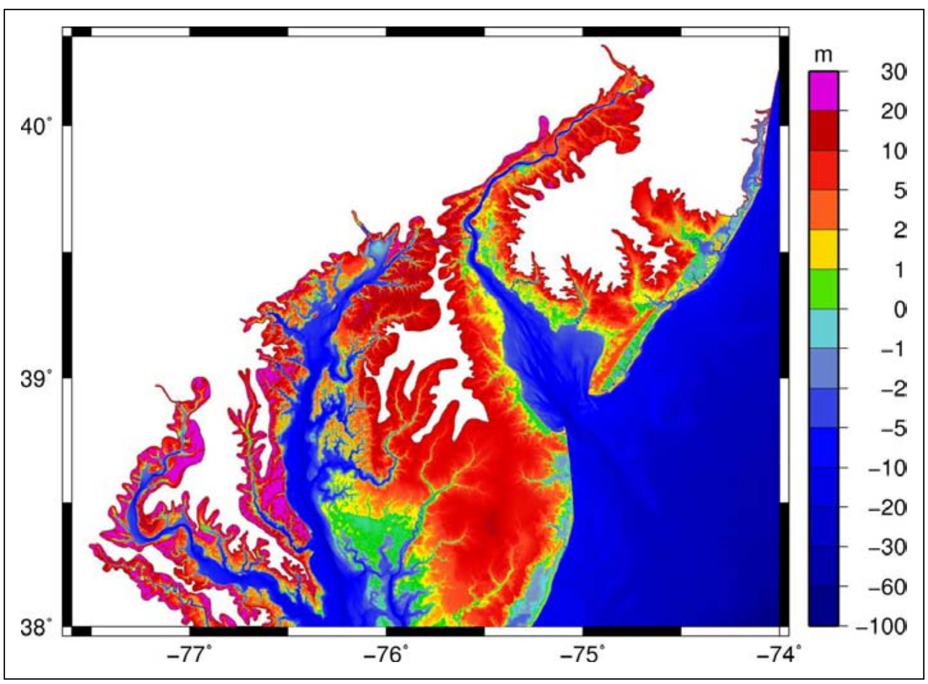


Figure 2.4 ADCIRC mesh elevation contours, meters NAVD88, of the northern portion of the FEMA Region III domain. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

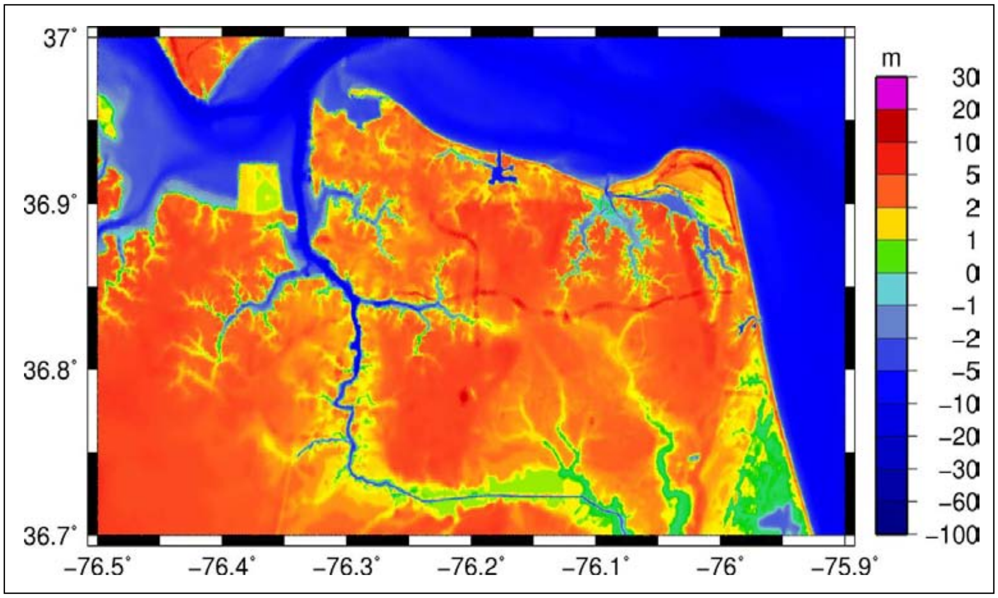


Figure 2.5 ADCIRC mesh elevation contours, meters NAVD88, in the area of Virginia Beach, Norfolk and Hampton, Virginia. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

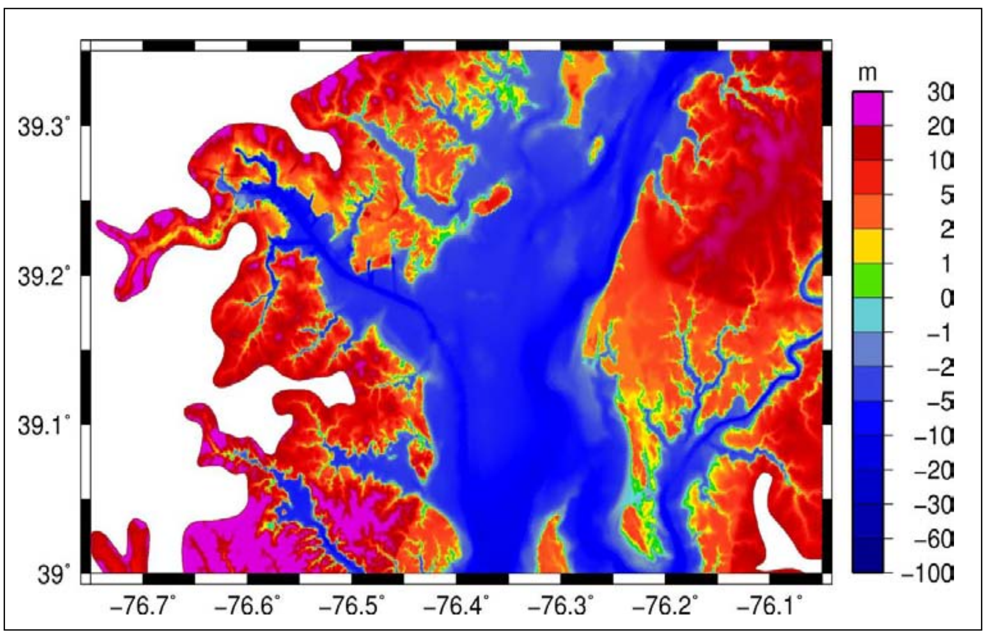


Figure 2.6 ADCIRC mesh elevation contours, meters NAVD88, in the area of Baltimore, Maryland. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

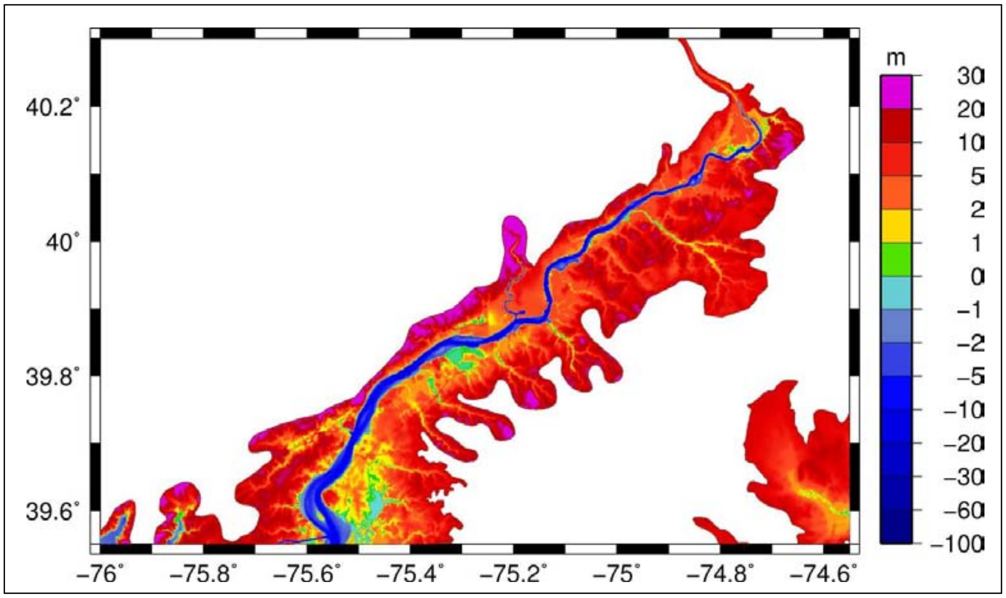


Figure 2.7 ADCIRC mesh elevation contours, meters NAVD88, in the area of Wilmington, Delaware; Philadelphia, Pennsylvania; and Trenton, New Jersey. Brown lines denote mesh boundaries. Positive elevations represent topographic values. Negative elevations represent bathymetric values.

The computational mesh has been constructed to provide sufficient resolution for the tidal, wind, atmospheric pressure, and riverine flow forcing functions from the ocean basins to the coastal floodplain. Efficient and effective resolution of tidal response within the basins and on the shelf is determined by tidal wavelength and topographic length scale criteria. Based on propagation of the predominant tidal wavelength for the $M_2$ tide, the wavelength criteria determines the ratio of wavelength ($\lambda$) to node spacing $\Delta x$. A minimum wavelength-to-grid spacing ratio $\lambda_{M2}/(\Delta x)$ of at least 50 is required, and a more satisfactory value is closer to 100 (Westerink et al., 2008; Luettich and Westerink, 1995). The mesh also has increased resolution at the shelf. Shallower water generates shorter wavelengths and higher wave numbers, thus requiring more resolution to resolve the physical processes. The shelf has steep bathymetric gradients which require higher resolution than the deep Atlantic due to the topographic length scale relationship of water depth to bathymetric slope (Hagen et al., 2000; Hagen et al., 2001). The FEMA Coastal North Carolina storm surge model and EC2001 tidal model both resolve the shelf-break guided by a topographic length scale criteria to capture the higher localized wave number content. There are no published studies to date analyzing the relationship between mesh resolution and unstructured Simulating WAves Nearshore (SWAN) performance. However, increased shelf resolution has anecdotally shown better results when using the unstructured SWAN model (Dietrich et al., 2011). The SWAN+ADCIRC analysis published by (Dietrich et al., 2011) utilized mesh resolutions ranging from 200 meters to 500 meters in wave breaking zones and coarser resolution in deeper waters. The FEMA_R3_2011 mesh varies in resolution from approximately 50 meters to 3 kilometers from the shoreline to the 100 meter bathymetric contour.

Hurricane forcing and response are also examined to determine the level of resolution required to model hurricane effects accurately. In deep water, under-resolution of the inverted barometer forcing function results in under-prediction of the peak inverted barometer effect. This phenomenon, which involves smearing of the inverted barometric pressure effect, results from insufficient resolution for the interpolation of the input atmospheric pressure field onto the hydrodynamic mesh. Enhanced resolution in shelf waters adjacent to hurricane landfall locations is critical because under-resolution can lead to over-prediction of peak storm surge (Blain et al., 1998).

The FEMA_R3_2010 computational mesh contains more than 1.7 million nodes and nodal spacing varies significantly throughout the mesh. Grid resolution varies from approximately 19 to 24 km in the deep Atlantic Ocean to about 30 m in the study region. The high grid resolution required for the study region leads to a final grid with more than 90 percent of the computational nodes placed within or upon the shelf adjacent to FEMA Region III, enabling sufficient resolution while minimizing the cost of including such an extensive domain. Therefore, use of a large-scale domain only adds 10 percent to the computational cost of the simulations. The result, however, is the application of highly accurate boundary conditions and full dynamic coupling between all scales from basins to inlets.

The mesh design provides localized refinement of the Chesapeake Bay and Delaware Bay coastal floodplains and of the important hydraulic features. The level of detail in the study region is very high, with nodal spacing reaching as low as 30 m in the most highly refined areas. Figures 2.8 through 2.14 show the distribution of the element size across the mesh for different areas. The FEMA_R3_2010 mesh is refined locally to resolve features such as inlets, rivers, navigation channels, coastal dunes, and local topography/bathymetry. Previous mesh-resolution sensitivity studies

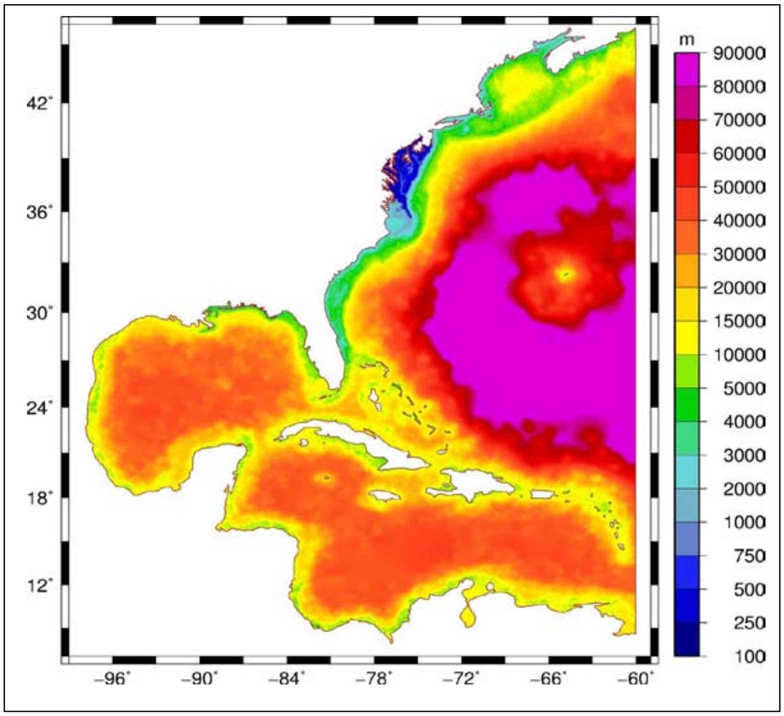


Figure 2.8 ADCIRC mesh element resolution in meters. Brown lines denote mesh boundaries.

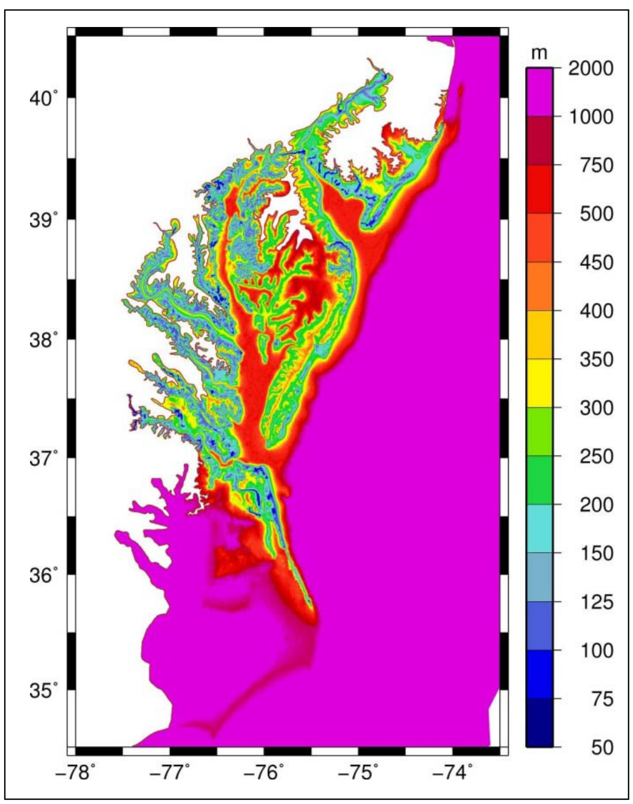


Figure 2.9 ADCIRC mesh element resolution in meters in the FEMA Region III domain. Brown lines denote mesh boundaries.

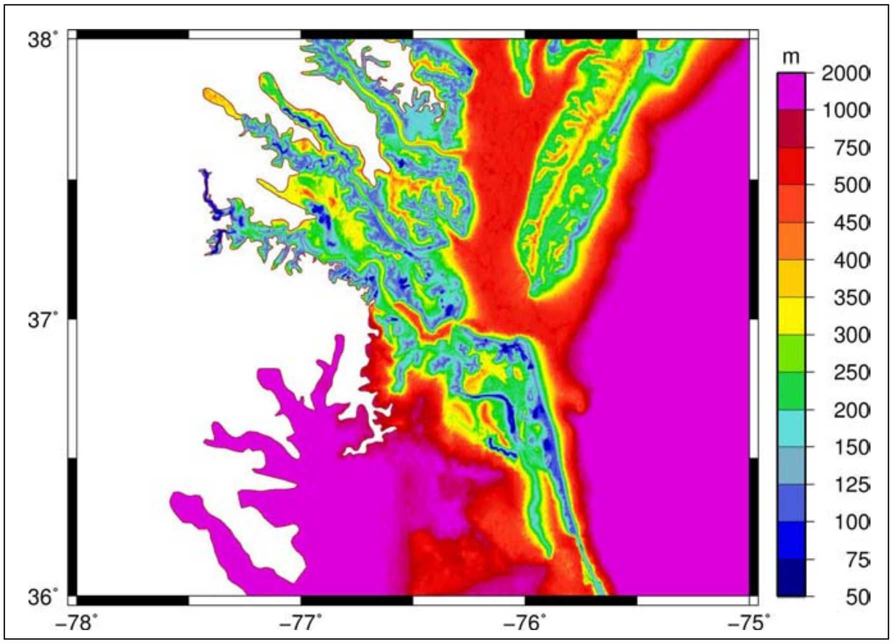


Figure 2.10 ADCIRC mesh element resolution in meters in the southern portion of the FEMA Region III domain. Brown lines denote mesh boundaries.

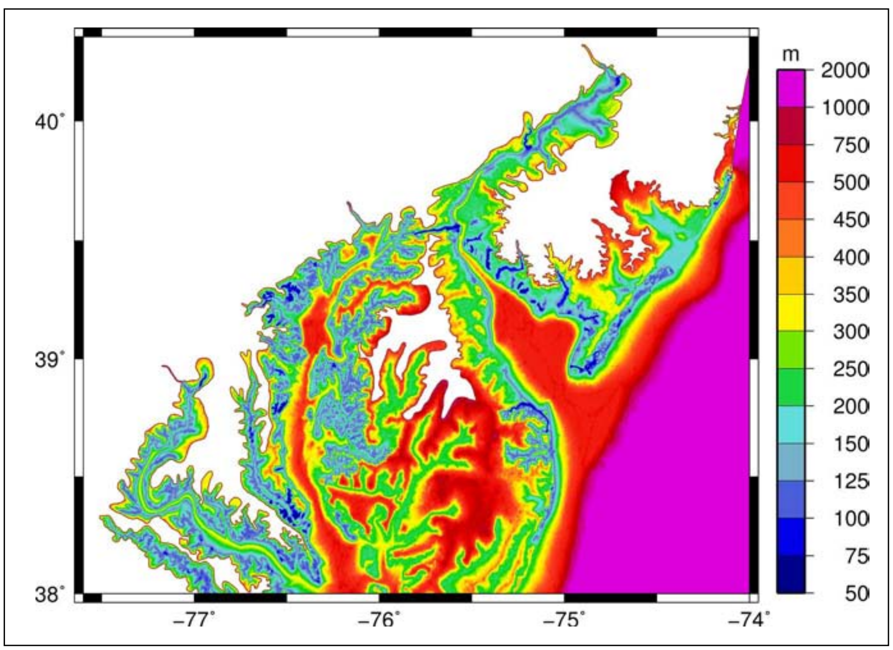


Figure 2.11 ADCIRC mesh element resolution in meters in the northern portion of the FEMA Region III domain. Brown lines denote mesh boundaries.

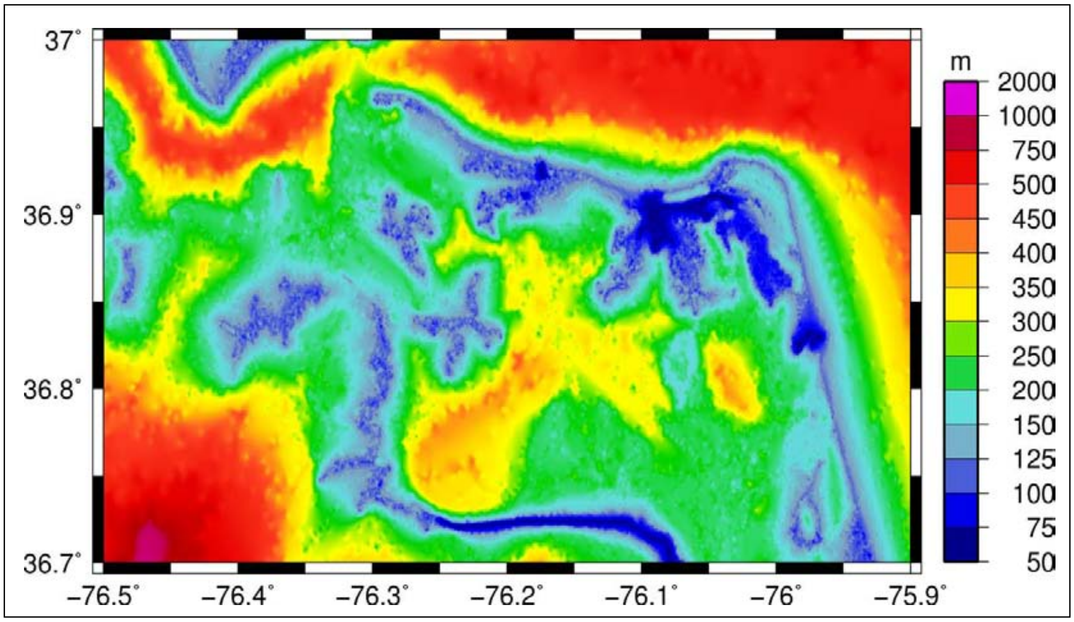


Figure 2.12 ADCIRC mesh element resolution in meters in the area of Virginia Beach, Norfolk and Hampton, Virginia.

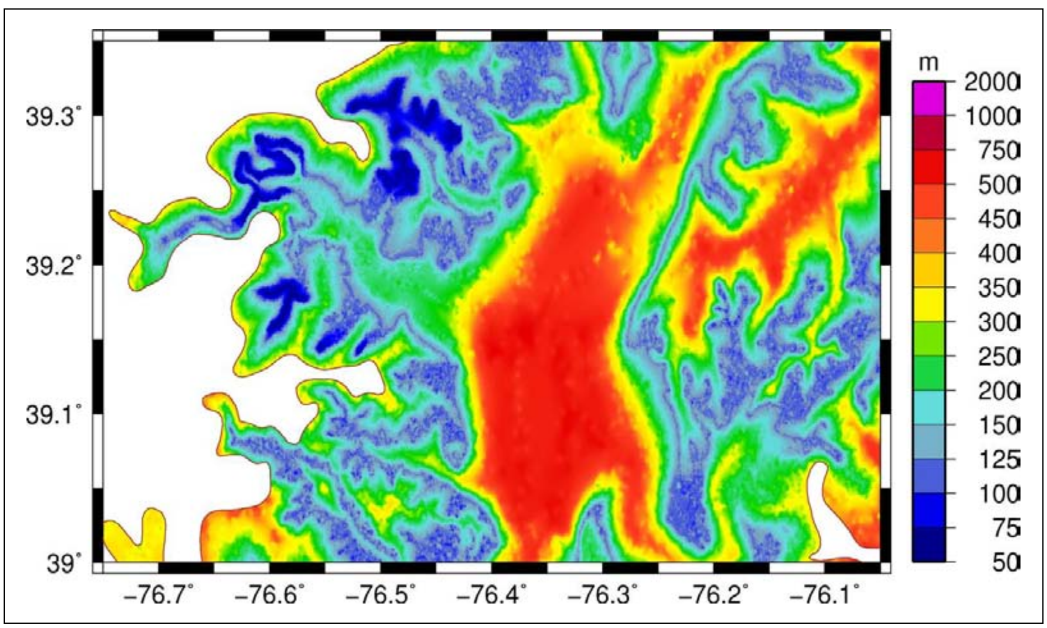


Figure 2.13 ADCIRC mesh element resolution in meters in the area of Baltimore, Maryland. Brown lines denote mesh boundaries.

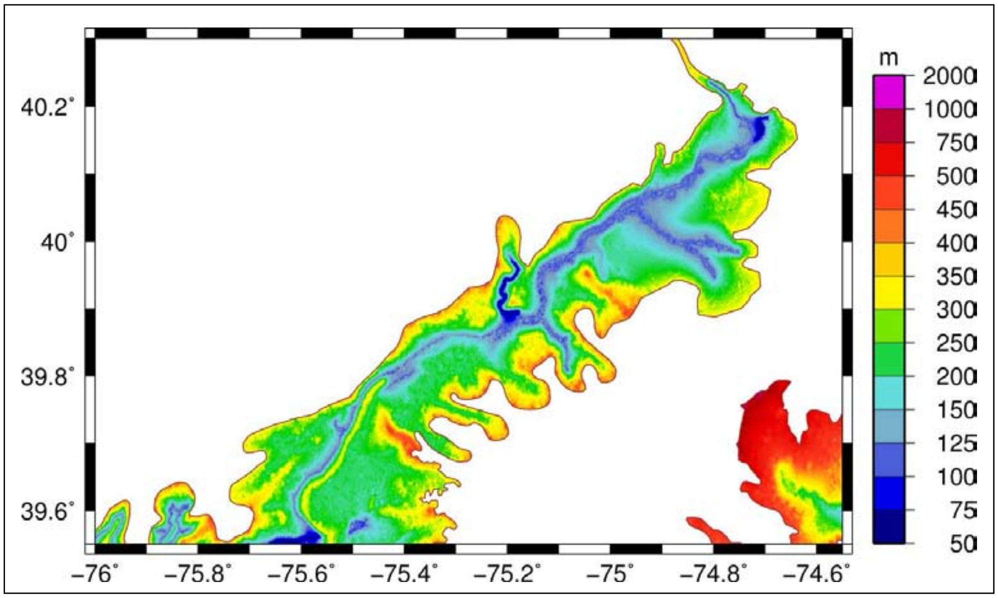


Figure 2.14 ADCIRC mesh element resolution in meters in the area of Wilmington, Delaware; Philadelphia, Pennsylvania; and Trenton, New Jersey. Brown lines denote mesh boundaries.

applying the ADCIRC model to the rivers and to the Lake Pontchartrain-Lake Borgne inlet system of Coastal Louisiana indicate that under-resolution severely dampens tidal and surge propagation into rivers and inlets (Feyen et al., 2000). Regardless of channel dimensions, a small number of meshing stipulations were adhered to while mapping inland waterway bathymetry in the model. The most stringent constraint was to set a maximum resolution of 30 m throughout the mesh to control computational cost. A finer level of resolution creates additional nodes, elements, and thus calculations per time step. In addition, a smaller time step could be necessary within the ADCIRC model to accommodate for the high spatial resolution. A Courant, Friedrichs, Lewy parameter less than 0.5 is desired when running the ADCIRC model. A second important attribute of channel meshes is the placement of a minimum number of nodes across a channel. When possible, at least five nodes were placed across a channel for two reasons. First and foremost, channels require high resolution to adequately capture bathymetric characteristics. Second, multiple nodes are placed within the channel to prevent the ADCIRC wetting and drying algorithm from artificially reducing the conveyance of the channel. In spite of this, it should be noted that computational cost was deemed very important, thus the 100-foot minimum discretization requirement was obeyed more stringently than the five-node requirement. Rivers that are less than 150 m across have fewer than five nodes across each cross section.

## Bathymetric/Topographic definition

Geometry, topography, and bathymetry in the FEMA_R3_2010 ADCIRC model were all defined to replicate prevailing conditions. Open ocean bathymetric depths were defined by the earlier North Atlantic Model used in the NC mesh (Luettich and Blanton, 2008) and the EC2001 U.S. East Coast and Gulf of Mexico tide model (Mukai et al., 2002). Additionally, Barnegat Bay in New Jersey was defined by the bathymetry in a previous NOAA ADCIRC model. Topography and bathymetry from Morehead City, North Carolina to Albemarle Sound was defined using the FEMA Coastal North Carolina storm surge model (Luettich and Blanton, 2008). Mesh nodes that lie within the extents of the DEM created for this project described in Submittal 1.1 (Forte et al., 2010), largely utilized the DEM to define mesh elevations. Figure 2.15 shows the various data sources utilized to define mesh bathymetry and topography.

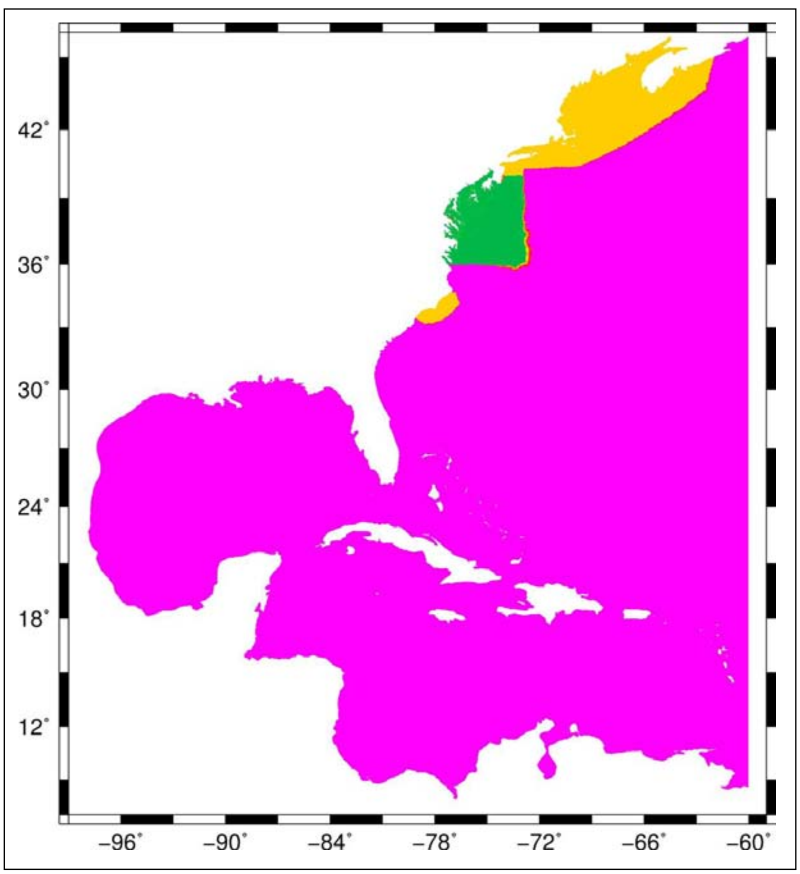


Figure 2.15 Data sources utilized to define mesh bathymetry and topography. Nodes shaded in green utilized DEM elevations, those in magenta used the North Carolina FEMA ADCIRC mesh, and those in light orange used the EC2001 mesh.

Mesh elevations within the study area were defined via one of four methods:

- Mesh scale averaging of DEM elevations
- Direct sampling of DEM elevations
- Maximum elevation within a control volume
- NOAA Historical Charts
- Engineering Documents

Figures 2.16 through 2.21 depict the methodology utilized to define each mesh node elevation. The following sections describe the elevation application procedure.

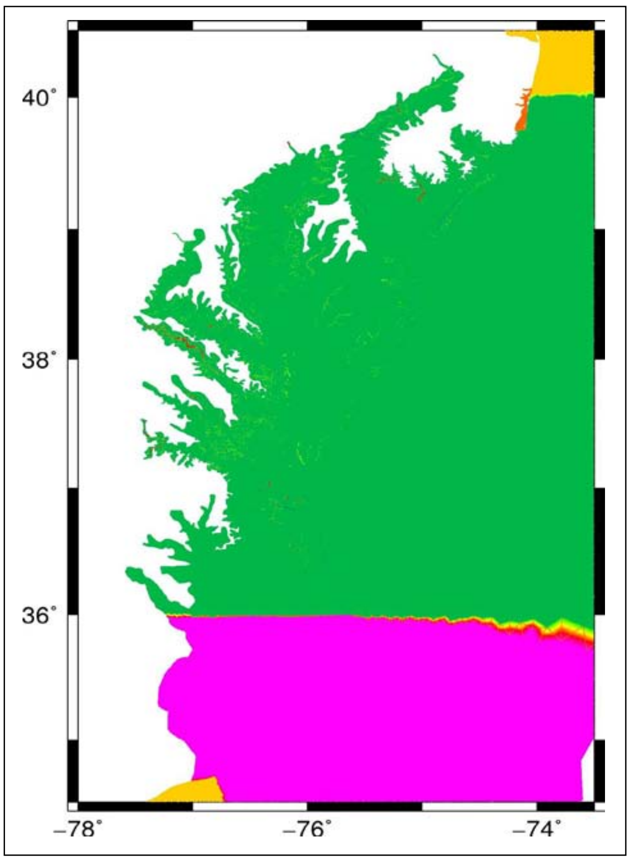


Figure 2.16 Nodal elevation definition methodologies in the FEMA Region III domain. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, those in red used additional sources, those in magenta used the North Carolina FEMA ADCIRC mesh, those in light orange used the EC2001 mesh and those in dark orange used the NOAA tidal mesh.

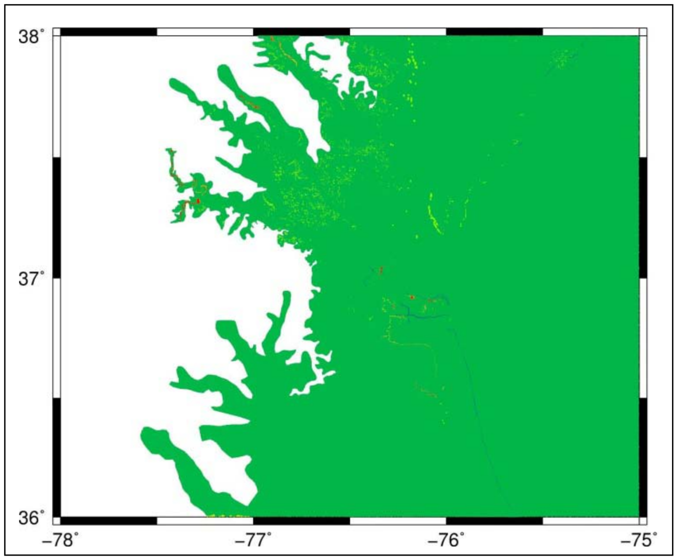


Figure 2.17 Nodal elevation definition methodologies in the southern portion of the FEMA Region III domain. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, and those in red used additional sources.

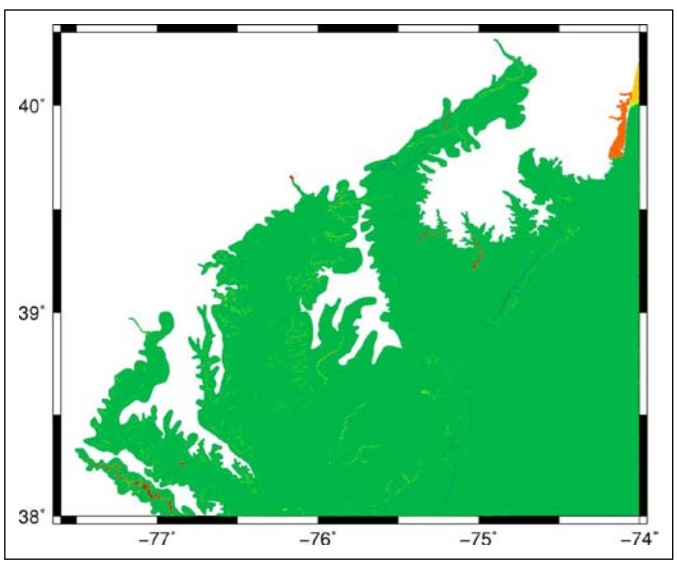


Figure 2.18 Nodal elevation definition methodologies in the northern portion of the FEMA Region III domain. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, those in red used additional sources, those in light orange used the EC2001 mesh and those in dark orange used the NOAA tidal mesh.

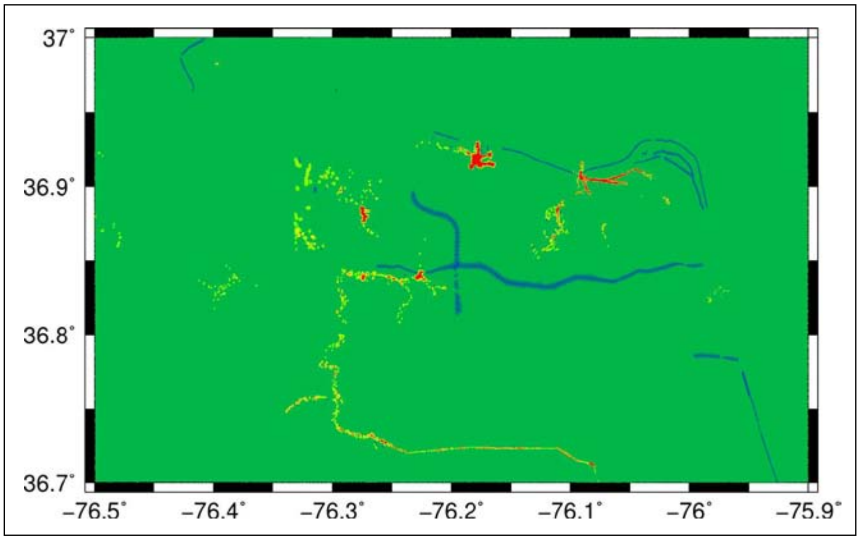


Figure 2.19: Nodal elevation definition methodologies in the area of Virginia Beach, Norfolk and Hampton, Virginia. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, and those in red used additional sources.

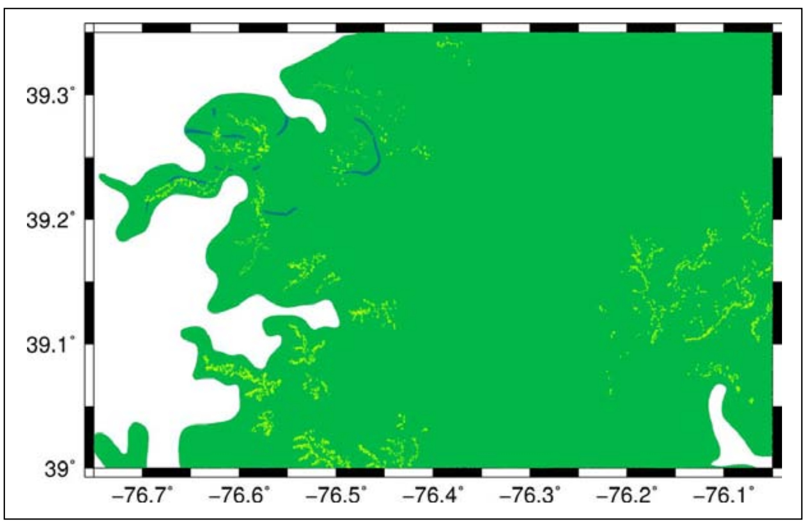


Figure 2.20 Nodal elevation definition methodologies in the area of Baltimore, Maryland. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, and those in red used additional sources.

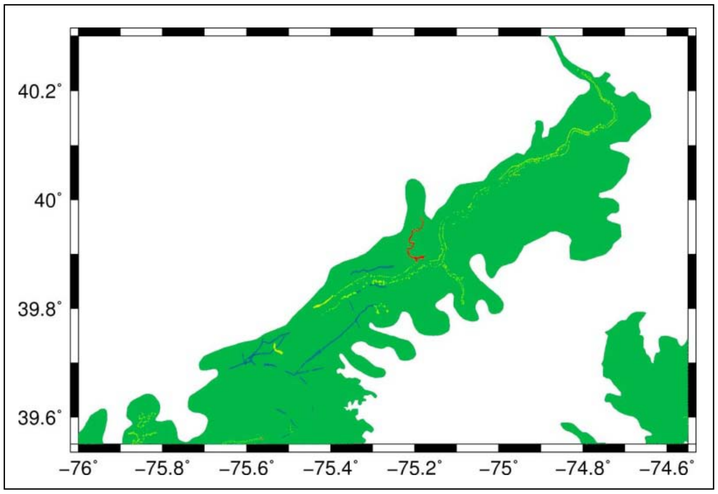


Figure 2.21 Nodal elevation definition methodologies in the area of Wilmington, Delaware; Philadelphia, Pennsylvania; and Trenton, New Jersey. Nodes shaded in green utilized mesh scale averaging of DEM elevations, those in yellow utilized direct sampling of DEM elevations, those in blue utilized the maximum DEM elevation within a control volume, and those in red used additional sources.

### Mesh scale averaging of DEM elevations

The vast majority of mesh nodes within the DEM domain were defined using a mesh scale averaging technique. The elevation data were applied to the mesh by searching for all DEM data points within a control volume. As shown in Figure 2.22, the control volume is sized by the mid-points of all the elements to which the node is attached. Thus as elements increase in size, their midpoints are spaced further apart and the control volume increases in size relative to the mesh resolution. The elevation values for all the collected DEM pixels in the control volume are averaged to generate the nodal value. Figure 2.22 show a schematic of how the averaging methodology is employed. This rectangular averaging paradigm was adopted to most efficiently apply DEM elevations to the mesh. The search algorithms to find all the DEM values within a regularly shaped space works significantly faster than an unstructured grid element cluster gather/averaging scheme. Given the number of on-mesh nodes and the tremendous size and density of the DEM, speed is critical. Additionally and most critically, is that the rectangular averaging scheme also accurately and effectively implements mesh scale averaging of elevation values onto nodes.

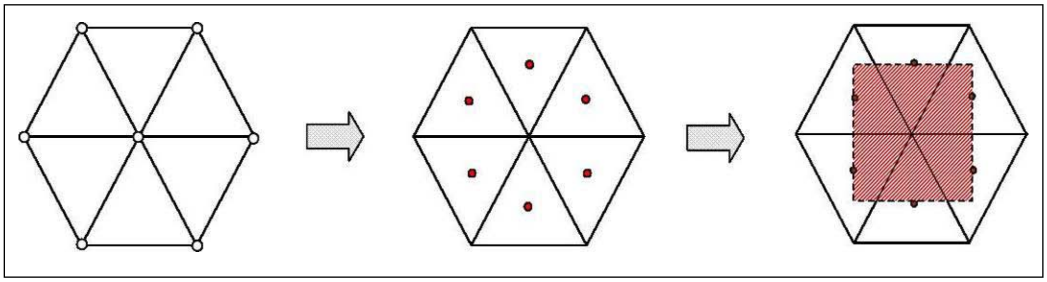

Figure 2.22 Sizing nodal control volume for DEM elevation definitions.

### Maximum elevation within a control volume

Mesh nodes aligned on crown locations of impediments, such as highways and dams, require extraction of crown elevations from the DEM. Similar to mesh scale averaged elevations, the elevation data were applied to the mesh by searching for all DEM data points within a control volume, as shown in Figure 2.22. The elevation values for all the collected DEM points in the control volume were sorted to locate the maximum value, which was then applied as the nodal value.

### Direct sampling of DEM elevations

Areas, such as narrow inland channels, are better suited for direct sampling from the DEM than area averaging. Often, narrow inland channels are important components to the conveyance of flood waters overland. In instances where the grid scale is too large to capture a channel bottom at multiple nodes across a channel, a narrow channel could be inadvertently averaged out of the mesh domain or unable to convey flow along a line of single nodes due to the configuration of the ADCIRC wetting and drying algorithm. Hence, for features such as narrow inland channels, direct sampling from the DEM is utilized to ascertain that critical conveyance features are included in the mesh. It should be noted that direct sampling refers to assigning a nodal elevation as the evaluation of the nearest DEM pixel.

### Additional sources

All ADCIRC nodes outside of the DEM domain were defined using the EC2001 U.S. East Coast and Gulf of Mexico tide model (Mukai et al., 2002) or the FEMA Coastal North Carolina storm surge model (Luettich and Blanton, 2008) as mentioned in Section 2.1. Additionally, there are nodes within the DEM domain that require assignment of elevations not derived from the DEM itself. There are two cases that are most commonly requiring nodal elevation adjustments within the DEM domain.

The first are areas in which accurate information was not available when generating the DEM or the available data sources were not sufficient to include in the DEM. Examples are areas that only nautical charts or very discrete survey data are available. In these cases, the best available data, either charts or limited survey, were utilized to manually assign mesh nodal elevations. Channels were outlined using satellite imagery and mesh elements were aligned with the banks. Bathymetric elevations in those channels were assigned by linearly interpolating the available survey data or approximating the elevation using nautical charts, instead of using the available DEM elevations.

The second types of cases are areas in which the mapped elevations were not deemed optimal for model operation. An example would be a narrow low-lying area. The wetting and drying algorithm in ADCIRC requires all nodes in an active element be wetted. Thus a minimum of 2 or 3 adjacent rows of elements are required in the ADIRC model to activate elements in a wetting front and accurately propagate flood waters up a narrow channel. In these areas, the banks of narrow channels were artificially lowered when necessary to ensure that a wetting front is not constrained from propagating by the ADCIRC wetting and drying algorithm. Edge of bank values are typically set to 1 foot below the 0.0 NAVD88 elevation.

# 3 Computational system

The computational system for the FEMA Region 3 floodplain-mapping project uses state-of-the-art numerical models for wind, wave, and surge to compute storm-driven water levels for the coastal area. The model suite consists of the Applied Research Associates Hurricane Boundary Layer (HBL) model (Vickery et al, 2009) for tropical storms (hurricanes) and Oceanweather Inc's Interactive Objective Kinematic Analysis system (IOKA, Cox et al, 1995) wind and pressure fields for extratropical storms. Coastal water levels and waves are simulated using the storm surge and tidal model ADvanced CIRCulation for Model for Oceanic, Coastal and Estuarine Waters (ADCIRC, Westerink et al, 2008) and the new unstructured version of Simulating WAves Nearshore (unSWAN) (Zijlema, 2010). The overall modeling approach is similar to recent FEMA-sponsored projects in North Carolina, Louisiana and Mississippi (Dietrich et al., 2009 and Bunya et al., 2010). Computer scripts manage each simulation in terms of pre- and post-processing of input and output files, submission of each simulation to the parallel computer clusters, and archival of the solutions. An overview of the models used is given in Table 3.1.

Table 3.1 Models used in the Region 3 Computational System.

| Model | Objective | Geographic Setup |
|---|---|---|
| IOKA | Provide wind/pressure for extra-tropical storms | Regional-scale |
| HBL | Provide wind/pressure for tropical storms | Regional-scale |
| ADCIRC | Computes wind and wave driven storm surge | Western North Atlantic, with high-resolution in Region 3 coastal and shelf waters. |
| unSWAN | Computes wind-driven wave field, provides wave-induced force to ADCIRC | Western North Atlantic, with high-resolution in Region 3 coastal and shelf waters. |

## Wind/Pressure: Applied research associates hurricane boundary layer (HBL) and oceanweather interactive objective kinematic analysis (IOKA) models

Two different methods are used to simulate the extratropical and tropical storms that create significant flood events in the region. Oceanweather provides the wind and pressure fields for the extratropical storms and for all validation storms from their IOKA system. These winds represent a 30-minute average at a 10m elevation. A factor of 1.09 is then applied to convert the winds to a 10-minute average. Wind and pressure fields are specified in OWI format for both a "basin" (far-field) grid and a higher-resolution "region" (near-field) grid. The basin grid covers the area shown in Figure 3.1 with a spatial resolution of 1/8 degree at a 30-minute time interval. The region grid covers the Region 3 area with a resolution of 1/40 degree at a 15-minute time interval. A more detailed example of this product is shown in Figure 3.2.

The Applied Research Associates Hurricane Boundary Layer (HBL) model (Vickery et al, 2009) is used to compute 10-meter elevation, 10-minute average wind velocity and determines pressure distribution for a defined spatial region. The HBL model validation process is well documented as presented in (Vickery et al., 2000, and Vickery et al., 2009). The input to HBL is a storm track in the format of a hur file, which specifies the time (YYYY, MM, DD, HH), position (lat, long), central pressure, radius to maximum winds (RMW), Holland-B parameter, and the far field pressure. The spatial coverage of the HBL simulated wind and pressure fields is the same as that for the extratropical wind and pressure field coverage, shown in Figure 3.1.

From the standpoint of the surge/wave modeling system, identical modeling setups are used for the validation runs and the production runs. Hence, no distinction is made between a tropical and extratropical wind field or between a validation and production storm simulation.

## Waves: Unstructured SWAN

The coastal wave model Simulating Waves Nearshore (SWAN) is a third-generation, phase-averaged numerical wave model for the simulation of waves in waters of deep, intermediate and finite depth (Booij et al., 1999, Rogers et al., 2003, Zijlema and van der Westhuysen, 2005). Recently, the SWAN model has been expanded to operate with triangular finite elements (Zijlema, 2010). The primary result is that the SWAN model uses the exact same model mesh generated for ADCIRC. Additionally, the ADCIRC and unstructured SWAN models have been formally coupled at the source code level. This obviates the need for complicated and time-consuming file sharing, which has typically been used for "loose" coupling of ADCIRC and the regular-gridded version of SWAN.

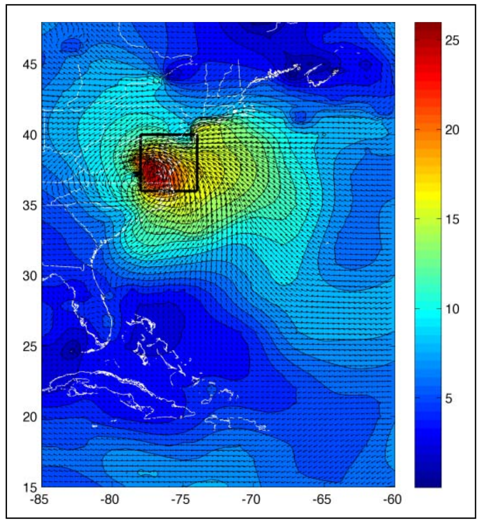


Figure 3.1 Coverage area of the OWI basin-scale grid for the project. The wind speed m/s (color) and direction (vectors) are shown for Hurricane Isabel after landfall on the North Carolina Coast.

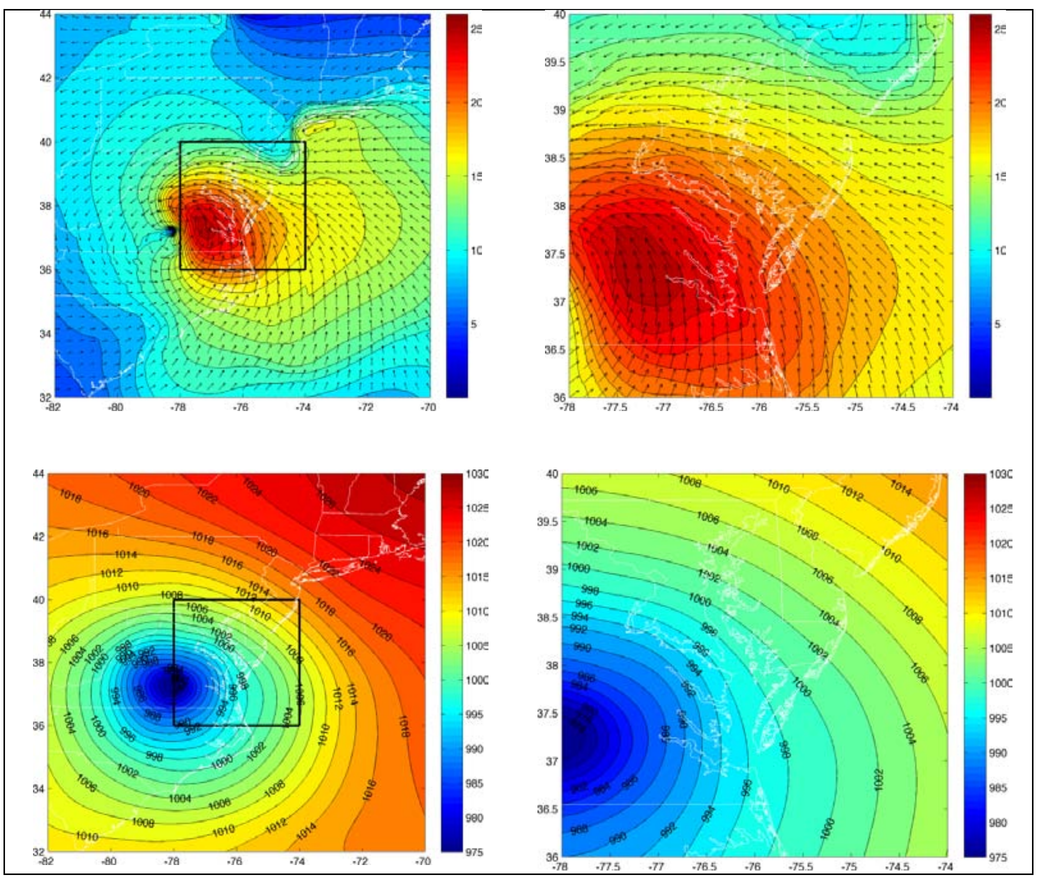


Figure 3.2 Detailed example of the IOKA wind and pressure fields from the Hurricane Isabel validation storm. The top row shows the wind speed m/s (color) and unit direction (vectors). The bottom row shows the pressure. A portion of the “basin” grid is shown in the left column, and the “region” grid is shown in the right column.

Unstructured SWAN is used in this project to compute the wave-induced stresses needed for total storm surge computation by ADCIRC. Wave breaking in shallow water adds to the mean currents that push water towards the shore. The wave spectra are computed at the ADCIRC nodal locations, and wave-induced stresses are communicated to ADCIRC in memory (as opposed to files). Wind forcing and water level at each ADCIRC node is passed from ADCIRC to SWAN for each SWAN computational step. Radiation stresses are then passed back to ADCIRC. The coupling interval is generally set to 600 seconds, meaning that information is exchanged every 10 simulated minutes. Details of the coupled implementation can be found in Dietrich et al. 2011. The saved output at all computation points includes the wave radiation stress, significant wave height, and wave period. SWAN model documentation, including the unstructured version, is available at: http://vlm089.citg.tudelft.nl/swan/index.htm

## Surge: ADCIRC

The storm surge simulations are performed using the state-of-the-art coastal circulation model ADCIRC (Luettich et al., 1992; Westerink et al., 2008), version 49. ADCIRC solves the vertically integrated shallow water equations in generalized wave continuity equation form. The equations are solved using a Galerkin finite element discretization in space with linear basis functions applied on triangular elements and a three level finite difference discretization in time. The model domain covers the North Atlantic region west of 60 deg W. The ADCIRC grid in the project region is shown in Figure 3.3 and detailed in section 2 above.

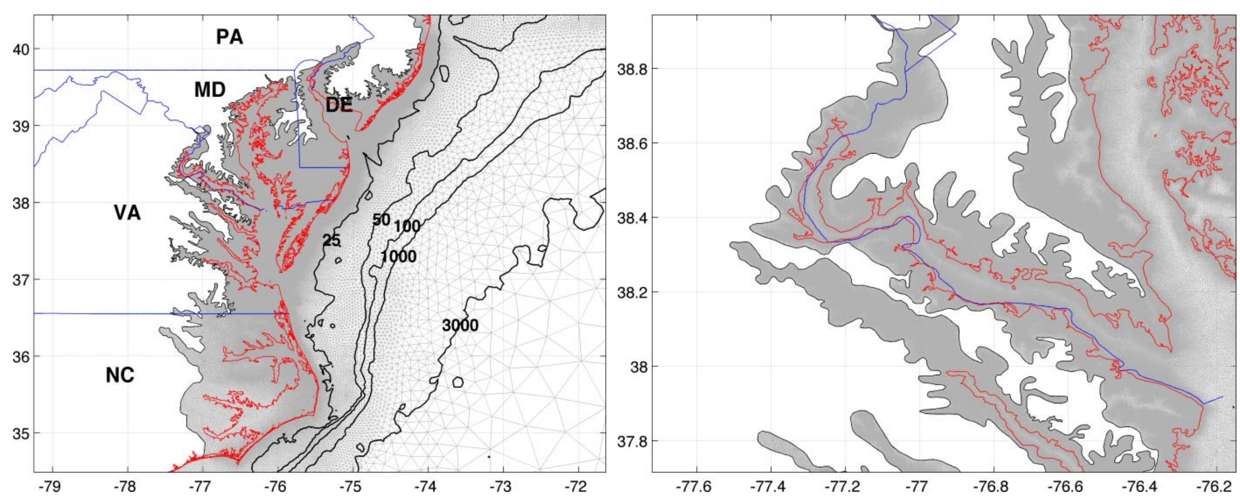


Figure 3.3 ADCIRC grid in the FEMA Region 3 coastal region. (Left) Portion of grid in the Region. The 25, 50, 100, 1000, and 3000 m bathymetric contours are shown. (Right) Detail of Potomac River and surrounding area. The red line is nominally mean sea level.

Information on the land surface elevation (from the DEM), frictional characteristics, roughness lengths and canopy cover are specified at the vertices (nodes) of each triangle. Forcing includes tidal amplitudes and phases on the open boundary (at 60 deg W), and wind stress, surface atmospheric pressure gradient, and wave stress gradients. Application of ADCIRC in this FEMA Region 3 study is consistent with other recent FEMA-sponsored projects in North Carolina and the Gulf of Mexico. The inland extent of the grid approximates the 15-m topographic elevation line. Near shore resolution is about 50 m and grades out to 2-10 km on the outer continental shelf.

## Computational resources

Project simulations (tidal/storm validation and production synthetic runs) are performed on RENCI's Dell Nehalem cluster called Blue Ridge, a 160 node, 8- to 12-core high-performance computer with an average storm simulation runtime of approximately 3.5 hours. Model simulations are controlled by a set of shell scripts that stage each simulation, synchronize model timings, and interact with the high-performance computer to schedule simulations and verify completion of each simulation. Main outputs from each simulation are stored for analysis. This includes the time series of water levels and velocities, significant wave heights, peak periods, and mean directions. A complete list of files is given in Table 3.2.

Table 3.2 File Storage Manifest.

**Tidal validation simulation:**

- ADCIRC Grid files
    - fort.14 ADCIRC grid file
    - fort.15 input parameter file
    - fort.13 nodal attribute file
- Results for the tidal simulation
    - Harmonic analysis output files
        - fort.51 station tidal harmonic analysis
        - fort.53 global tidal harmonic analysis
    - fort.63 global output water level time-series file
- Tide gage data

**Validation and production storm simulations:**

- Static model input files: (ADCIRC grid and nodal attributes, parameter files, etc).
- Wind model track files and wind/pressure fields for each storm
- All ADCIRC "fort" input files used for each simulation:
    - fort.15 input parameter file
    - Atmospheric forcing files
        - fort.22 OWI control file
        - fort.221 atmospheric pressure file
        - fort.222 wind velocity file
        - fort.223 regional atmospheric pressure file for IOKA
        - fort.224 regional wind velocity file for IOKA
    - Wave radiation stress files: rads.64. This is the global output file for the radiation stress gradients computed by unstructured SWAN;
    - fort.26 unstructured SWAN control file
- Result files for each storm:
    - ADCIRC-only and ADICRC+SWAN simulations:
        - fort.63 global water level time-series file
        - fort.73 global atmospheric pressure time-series file
        - fort.74 global wind velocity time-series file
        - Maximum elevation file for each storm simulation.
    - SWAN:
        - Significant wave height field (HSIGN)
        - Wave Period field (PER)
        - Wave Direction (DIR)
        - Station output used for validation analysis

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**14. ABSTRACT**

The Federal Emergency Management Agency, Region III office, has initiated a study to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia including the Atlantic Ocean, Chesapeake Bay including its tributaries, and the Delaware Bay. This effort is one of the most extensive coastal storm surge analyses to date, encompassing coastal floodplains in three states and including the largest estuary in the world. The study will replace outdated coastal storm surge stillwater elevations for all Flood Insurance Studies in the study area, and serve as the basis for new coastal hazard analysis and ultimately updated Flood Insurance Rate Maps (FIRMs). Study efforts were initiated in August of 2008, and are expected to conclude in 2010.

The storm surge study will utilize the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional hydraulics. ADCIRC will be coupled with 2-dimensional wave models to calculate the combined effects of surge and wind-induced waves. A seamless modeling grid was developed to support the storm surge modeling efforts. This report, the second of three reports comprising the required Submittal 1 documentation, provides a detailed overview of the construction of the modeling mesh and the development of an integrated computational system for FEMA Region III storm surge modeling.

**15. SUBJECT TERMS**

| | | |
|---|---|---|
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| FEMA Region III Storm Surge Study | Storm surge computational system | Unstructured grid |
| | Storm surge modeling | Wave modeling |

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